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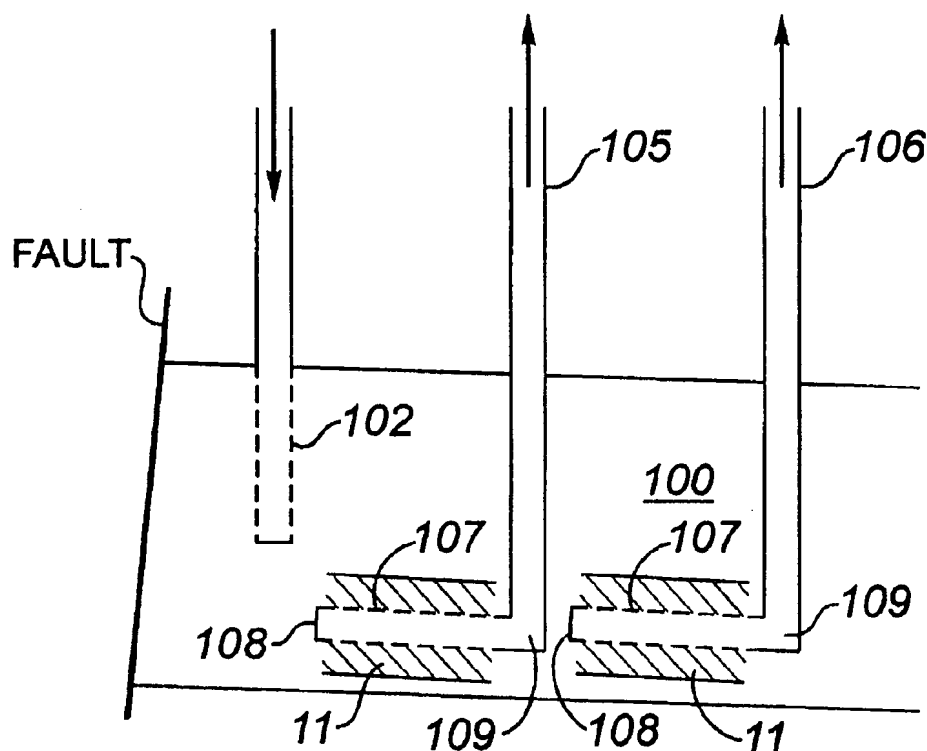
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(54) Titre : PROCESSUS DE VALORISATION IN SITU DES CHAMPS PETROLIERS  
(54) Title: OILFIELD IN-SITU UPGRADING PROCESS



(57) Abrégé/Abstract:

A well configuration is provided comprising an injection well completed relatively high in an oil reservoir and a production well completed relatively low in the reservoir. The production well has a horizontal leg oriented generally perpendicularly to a generally linear and laterally extending, upright combustion front propagated from the injection well. The leg is positioned in the path of the advancing front. Oil upgrading catalyst has been emplaced along the horizontal leg. The production well is maintained open, thereby providing a low pressure sink which induces the front to advance along the leg. The hot combustion gases react with the commingled oil over the catalyst to provide in situ upgrading.



1                                    **ABSTRACT OF THE DISCLOSURE**

2                    A well configuration is provided comprising an injection well completed  
3 relatively high in an oil reservoir and a production well completed relatively  
4 low in the reservoir. The production well has a horizontal leg oriented  
5 generally perpendicularly to a generally linear and laterally extending, upright  
6 combustion front propagated from the injection well. The leg is positioned in  
7 the path of the advancing front. Oil upgrading catalyst has been emplaced  
8 along the horizontal leg. The production well is maintained open, thereby  
9 providing a low pressure sink which induces the front to advance along the  
10 leg. The hot combustion gases react with the commingled oil over the  
11 catalyst to provide in situ upgrading.

## OILFIELD IN-SITU UPGRADING PROCESS

### FIELD OF THE INVENTION

This invention relates to a catalytic in situ process for upgrading hydrocarbons in an underground reservoir. More particularly, it relates to a process in which a catalyst is placed along the horizontal segment of a horizontal production well operating in a toe-to-heel configuration, which enables carbon monoxide and/or hydrogen produced in the reservoir or injected into the reservoir with steam, to pass sequentially with reservoir oil over the catalyst, immediately prior to being produced.

### BACKGROUND OF THE INVENTION

Large supplies of heavy oil (ca. 8 to 15 degrees API) and medium oil (ca. 15 – 25 API) exist throughout the world, most notably in Venezuela, Canada and the U.S.A.. Significant deposits are also to be found in the North Sea, China and Romania. The composition of the crude oil barrel is inexorably moving towards this heavier material, but it is relatively uneconomic to produce. Without upgrading to produce an oil of lighter composition, *i.e.* containing more white oil distillates (gasoline, diesel, etc.), heavy oil has very limited potential, historically trading at around \$9.00 below the price of conventional oil. While surface upgrading technology (H-Oil, Vega-Combi or LC Fining processes) is possible, the payout time on the very large investment required is long (ca. ten years), which is discouraging to commercialization.

1           In situ oil upgrading has several advantages over conventional surface  
2 upgrading technologies. Because in situ upgrading (reaction occurring  
3 underground) can be implemented on a well-by-well basis, there is no need  
4 for large capital-intensive projects. Rather, the size of an in situ project for a  
5 particular field can be tailored to available production rates. Thus, in situ  
6 upgrading is practical even for those fields deemed too small to provide  
7 sufficient production for conventional surface upgrading processing.  
8 Additional advantages for in situ upgrading include the production of a more  
9 desirable and valuable product, ease in shipping and pipelining (minimum of  
10 22 degree API gravity), and less demanding downstream processing  
11 (processable by a conventional refinery).

12           The requirements for an in situ upgrading process include: provision  
13 for a downhole bed of catalyst, achievement of appropriate high reaction  
14 temperatures and pressure at the catalyst bed, and mobilization of oil and co-  
15 reactants over the catalyst. Although the technologies to accomplish each of  
16 these tasks separately are known, their combination into a unified effective  
17 underground process has yet to be demonstrated in practice.

18           Because it is the most efficient method to achieve high temperatures in  
19 a reservoir without the direct application of heat, in situ combustion (ISC) is a  
20 promising oil recovery process to exploit in the development of an efficient  
21 and economical in situ upgrading process.

22           In-situ combustion processes are applied for the purpose of heating  
23 heavy or medium oil to mobilize it and drive it to an open production well for  
24 recovery. In general, the usual ISC technique used involves providing spaced  
25 apart vertical injection and production wells completed in a reservoir.

1 Typically, an injection well will be located within a pattern of surrounding  
2 production wells. Air, or other oxygen-containing gases are injected into the  
3 formation. The mixture of air or oxidizing gas and hydrocarbons is ignited, a  
4 combustion front is generated in the formation and the resulting combustion  
5 front is advanced outwardly toward the production wells. Or, alternately, a  
6 row of injection wells may feed air to a laterally extending combustion front  
7 which advances as a line drive toward a parallel row of production wells.

8 In both cases the operator seeks to establish an upright combustion  
9 front which provides good vertical sweep and advances generally horizontally  
10 through the reservoir with good lateral sweep. However the processes are  
11 not easy to operate and are characterized by various difficulties. One such  
12 difficulty arises from what is referred to as gravity segregation. The hot  
13 combustion gases tend to rise into the upper reaches of the reservoir. Being  
14 highly mobile, they tend to penetrate permeable streaks and rapidly advance  
15 preferentially through them. As a result they fail to uniformly carry out, over  
16 the cross-section of the reservoir, the functions of heating and driving oil  
17 towards the production wells. The resulting process efficiency therefore is  
18 often undesirably low. Typically the volumetric sweep efficiencies are less  
19 than 30%.

20 Weissman et al (Energy and Fuels, 1996, 10,883,889) have recently  
21 proposed a modified in situ combustion process using a vertical well  
22 production strategy, in which a catalyst bed is emplaced around the  
23 production well. They have reported the results of two ISC tests, from which  
24 they concluded that a heated bed of hydrocracker catalyst placed in the  
25 bottom section of an 1.8 m long, 0.1 m diameter combustion tube (a special

1 thin-walled reactor to simulate reservoir conditions), was effective in  
2 converting carbon monoxide, produced at the combustion front, and water,  
3 into carbon dioxide and hydrogen, via the water gas shift reaction. Not only  
4 was 50% of the sulphur removed by hydrodesulfurization ("HDS"), but there  
5 were also decreases in the oil density and viscosity obtained by the catalytic  
6 reaction. However, there were two main problems foreseen with this process:  
7 (1) the high retention of oil in the catalyst bed/gravel-pack (a large, one-place  
8 volume, with a vertical producer well), would lead to severe coking of the  
9 catalyst; and 2) the need to operate in either a cyclic mode (backflow on the  
10 injector well), or with a severe gas override condition to provide heat to the  
11 catalyst bed. Both processes possibly require supplementary downhole  
12 heating, which is both expensive and risky. Also, very importantly, the  
13 extremely acidic process gases (carbon dioxide and sulfur dioxide) entering  
14 the vertical production well, in combination with a temperature of over 300  
15 degrees Celsius, will cause severe corrosion to the vertical well, through  
16 which all production fluids must pass. In the case of deliberate combustion-  
17 gas override (which is used to achieve high temperatures at the vertical well),  
18 very poor reservoir sweep will be achieved and the possibility of oxygen  
19 breakthrough is increased, which could cause a serious explosion hazard. In  
20 the case that the proposed cyclic combustion process is used (again to  
21 achieve high temperatures at the vertical production well), the production  
22 rates will be at least halved because of the required air injection time in the  
23 same well. In summary, the two proposed catalytic in situ processes appear  
24 expensive and difficult to operate, and so are not felt to be feasible.

A new viscous oil recovery process has recently been developed which provides a substantial increase in reservoir sweep efficiency over that of the traditional ISC process. A combination of wells is used wherein the toes of horizontal production wells are the first segments to provide hydrocarbon  
5 production and to come into contact with the injected gases. Greaves and Turta, in U.S. Patent No. 5,626,191, disclose such a well configuration, which they call the "toe-to-heel" oil displacement process. The patent applies to any process where gases are injected to reduce the viscosity of oil in an underground reservoir, and includes oxidizing gases for in situ combustion,  
10 steam injection, steam injection along with other gases, and hydrocarbon solvent gases.

Many oilfield operators are reluctant to apply the in situ combustion process because of historically poor performance when used in a traditional vertical well drive mode, and so an in situ upgrading process that uses steam  
15 would be more appealing. Since some heavy or medium gravity oil reserves are found in relatively deep and hot reservoirs for example in the Orinoco Belt in Venezuela, high temperature steam can be utilized to provide the heat for an in situ upgrading process in some cases.

In summary of the prior art, it has been recognized as very desirable to  
20 achieve oil upgrading in an underground reservoir and the ISC process has been proposed as a possible heat source, but an effective process for implementing these steps has not yet been developed. The work underlying the present invention was undertaken to reach this objective. The present invention will now be described.





1 without significant over-riding. In the case of steam injection,  
2 the condensed water and heated oil will, along with any gases  
3 present, likewise flow down to the low pressure sink. In the  
4 case of in situ combustion the gases will be combustion gases:  
5 carbon monoxide, carbon dioxide, sulphur dioxide and water  
6 vapor.

7 Now, in accordance with the present invention:

- 8 • if an appropriate oil upgrading catalyst is placed along the  
9 horizontal leg of a production well arranged in toe-to-heel  
10 configuration, including any of within the leg, on the leg or in the  
11 reservoir around the leg; then
- 12 • hot combustion gases from an ISC process, or steam from a steam  
13 injection process combined with injected reducing gases, such as  
14 carbon monoxide or hydrogen, will react with the commingled oil  
15 over the catalyst at appropriate temperature and pressure and the  
16 oil will be substantially upgraded.

17 When compared in experimental runs with a conventional toe-to-heel  
18 ("TTH") in situ combustion process in accordance with the Greaves and Turta  
19 patent, without catalyst in the vicinity of the horizontal leg of the oil producing  
20 well, the present invention was found to be relatively characterized by:

- 21 • increased average API gravity of produced oil;  
22 • reduced oil viscosity;  
23 • reduced oxygen and carbon monoxide and increased carbon  
24 dioxide levels in the produced gas stream;  
25 • extensive hydrodesulfurization of the oil; and

1           • extensive hydrodemetallization of the oil.

2           Additionally, the present process benefits from being a single pass  
3 catalytic process so that the reactant oil and gases continuously access fresh  
4 catalyst. The distributed catalyst along the horizontal well maintains high  
5 conversion activity by virtue of sequential catalyst exposure caused by the  
6 advancing movement of the combustion front from the toe to the heel of the  
7 horizontal well.

8           Therefore, in broad terms, the invention is a process for upgrading oil  
9 in an underground reservoir while the oil is recovered through a production  
10 well, comprising: providing an injection well for injecting a gaseous fluid into  
11 the reservoir to form an advancing, laterally extending displacement front  
12 operative to reduce the viscosity of reservoir oil; providing at least one open  
13 production well having a horizontal leg completed relatively low in the  
14 reservoir and positioned substantially perpendicular to and in the path of the  
15 advancing front; emplacing oil upgrading catalyst along the leg's length;  
16 injecting the gaseous fluid into the injection well and advancing the  
17 displacement front along the leg; and producing the production well to recover  
18 upgraded oil from the reservoir.

19

20                                   DESCRIPTION OF THE DRAWINGS

21           Figure 1 is a perspective view schematically showing a sand pack with  
22 simulated vertical injection wells and a perpendicularly arranged, horizontal  
23 production well, said injection wells and production well being completed  
24 relatively high and low in the pack, respectively, as in the base case of the  
25 Greaves and Turta prior art, and reported below for Runs 971 and 972;

1           Figure 2 is a perspective view schematically showing a sand pack with  
2   simulated vertical injection wells and a perpendicularly arranged, horizontal  
3   production well, said injection wells and production well being completed  
4   relatively high and low in the pack, respectively, as in Figure 1, but with the  
5   placement of upgrading catalyst around the horizontal segment of the  
6   horizontal well, and reported below for Runs 975 and 976;

7           Figure 3a, 3b, 3c are top, side and end views of the test cell employed  
8   in demonstration of the present invention for the toe-to-heel process when  
9   operated in the catalytic upgrading mode in Runs 975 and 976;

10          Figure 4 is a flow diagram showing the laboratory set-up, including the  
11   test cell of Figures 3a – 3c, used to conduct the experimental runs reported on  
12   below;

13          Figures 5a and 5b show gas chromatographic spectra for Wolf Lake  
14   crude oil used in the test runs, and produced oil from the catalytic wet ISC  
15   Run 976 of the present invention, respectively;

16          Figure 6 is a plan view showing a preferred field embodiment of the  
17   well layout;

18          Figure 7 is a side cross-section taken along the line XII- XII of the well  
19   arrangement of Figure 6; and

20          Figures 8a, 8c and 8e are horizontal thermal contour plots for three  
21   layers in the sand pack after 6 hours of operation during Run 7 – Figures 8b,  
22   8d and 8f are vertical cross-section thermal contour plots.

## DESCRIPTION OF THE PREFERRED EMBODIMENT

The invention was developed in the course of carrying out an experimental investigation involving test runs carried out in a test cell or three dimensional physical model.

More particularly, a test cell 1, shown in Figures 3a, 3b and 3c was provided. The cell comprised a rectangular, closed, thin-walled stainless steel box 2. Dimension-wise, the box 2 formed a chamber 3 having dimensions 40 x 40 x 10 cm (total volume 16,000 c.c.). The thickness of each box wall was 4 millimeters. The chamber 3 was filled with a sand pack 4 consisting of a mixture of sand, clay, oil and water. The composition of the uniform mixture charged into the chamber 3 and other bed properties shown below in Table 1.

The porosity of the sand pack 4 was about 38.5% and the permeability was about 1.042 darcys.

The loaded cell box 2 was placed inside a larger aluminum box 5 and the space between them was filled with vermiculite powder insulation.

Sixty type K thermocouples 6, positioned at 6 cm intervals as shown in Figures 3a, 3b, 3c and 4, extended through the wall of the cell 1 into the sand pack 4, for measuring the three dimensional temperature distribution in the sand pack 4.

To compensate for heat losses, the cell 1 was wound with heating tape (not shown). This heat source was controlled manually, on demand, in response to the observed combustion peak temperature and adjacent well temperature values. The temperature at the wall of the cell was kept a few degrees Celsius less than the temperature inside the sand, close to the wall. In this way, the quasi-adiabatic character of the run was assured.

1           A cell heater 7 was embedded in the top section of the sand pack 4 at  
2   the air injection end, for raising the temperature in the region of the injection  
3   well 8 to ignition temperature.

4           Simulated air injection wells 8 were provided at the injection end of the  
5   cell 1. A simulated production well 9 was provided at the opposite or  
6   production end of the cell 1.

7           For Runs 975 and 976, a 0.25 inch diameter cylindrical catalyst bed  
8   was placed around the horizontal leg, whereas, for Runs 971 and 972, which  
9   constitute demonstrations of prior art for comparison purposes, the catalyst  
10   bed was omitted.

11          The positioning and vertical or horizontal disposition of the wells 8, 9  
12   are shown schematically in Figures 1, 2 and 3a – 3c for the four test runs  
13   reported on below. This well configuration is referred to as the direct line  
14   drive configuration. However, other well configurations are also  
15   contemplated, such as staggered line drive where the vertical injection wells  
16   are placed between the horizontal legs, or a horizontal injection well is placed  
17   relatively high in the reservoir to simulate the effect of a number of vertical  
18   injectors by having periodic perforations as a means to distribute the injectant  
19   gas. In the case that the reservoir heating is accomplished by injection of  
20   steam, the appropriate location of the steam injectors will be reservoir-specific  
21   and may not be high in the reservoir.

1           As shown in Figure 1 for non-catalytic Runs 971 and 972, a horizontal  
2 injection well 8 was placed relatively high in the cell, while the production well  
3 9 was horizontal and placed relatively low in the test cell with its toe slightly  
4 displaced from the injection well. Non-catalytic Runs 971 and 972 were a  
5 demonstration of prior art (Greaves and Turta) and were conducted for  
6 comparison purposes only. Run 971 was a dry ISC process, and Run 972  
7 was a wet ISC process. There was no catalyst present for these Runs.

8           As shown in Figures 2 and 3a – 3c, for catalytic Runs 975 and 976, a  
9 horizontal injection well 8, positioned laterally across the sand pack 4, was  
10 provided. The injection well was located relatively high in the sand pack. The  
11 production well 9 was horizontal, elongated, positioned low in the sand pack  
12 and had its toe adjacent to but spaced from the injection well. The horizontal  
13 production well 9 was arranged to be generally perpendicular to a laterally  
14 extending combustion front developed at the injection source. However, the  
15 toe 10 of the production well was spaced horizontally away from a vertical  
16 projection of the injection well. An elongated ring of catalyst, 11, was placed  
17 around the horizontal well 9.

18           The oil upgrading catalyst employed in Runs 975 and 976 was a  
19 standard hydrotreating/HDS catalyst manufactured by Akzo Chemie  
20 Nederland bv. Amsterdam, and identified as Ketjenfine 742-1, 3AQ.

21           Each of the injection and production wells 8,9 were formed of  
22 perforated stainless steel tubing having a bore 4 mm in diameter. The tubing  
23 was covered with 100 gauge wire mesh (not shown) to exclude sand from  
24 entering the tubing bore.

The combustion cell 1 was integrated into a conventional laboratory system shown in Figure 4. The major components of this system are now shortly described.

Air was supplied to the injection well 8 from a tank 19 through a line 20. The line 20 was sequentially connected with a gas dryer 21, mass flowmeter 22 and pressure gauge 23 before reaching the injection well 8. Nitrogen could be supplied to the injection well 8 from a tank 24 connected to line 20. Water could be supplied to the injection well 8 from a tank 27 by a pump 25 through line 26. Line 26 was connected with line 20 downstream of the pressure gauge 23. A temperature controller 28 controlled the ignition heater 7. The produced fluids passed through a line 30 connected with a separator 31. Gases separated from the produced fluid and passed out of the separator 31 through an overhead line 32 controlled by a back pressure regulator 33. The regulator 33 maintained a constant pressure in the test cell 1. The volume of the produced gas was measured by a wet test meter 34 connected to line 32. The liquid leaving the separator was collected in a cylinder 40.

Part of the produced gas was passed through an oxygen analyzer 36 and gas chromatograph 37. Temperature data from the thermocouples 6 was collected by a computer 38 and gas composition data was collected from the analyzer 36 and gas chromatograph 37 by an integrator 39.

1

TABLE 1

2

## BED PROPERTIES

Run Code	971	973	975	976
Bed Type	Uncon	Uncon	Uncon	Uncon
Sand Type	Silica. W50	Silica. W50	Silica. W50	Silica. W50
Sand wt%	97	97	97	97
Clay wt% kaolinite	3	3	3	3
Porosity %	38.5	38.5	38.5	38.5
Permeability (md)	1042	1042	1042	1042
S <sub>oi</sub> %	76	76	76	76
S <sub>wi</sub> %	17	17	17	17
S <sub>gi</sub> %	7	7	7	7
Initial Temperature (Deg C)	18	17	18	17

3

4

Air was injected at a rate of approximately 6.0 l/m. and ignition was

5

initiated using the heater 7. The tests were typically continued for up to 11

6

hours for the dry ISC Runs 971, 975 and for 7.5 hours for the wet ISC Runs

7

972, 976. In the runs where water was added, its rate was 0.025 l/m. Details

8

of the operating conditions are provided in Table 2.

9



1 TABLE 2  
2 OPERATING CONDITIONS

Run Code	971	972	975	976
Combustion Mode	Dry	Wet	Dry	Wet
Catalyst	no	no	yes	yes
Air flux (m <sup>3</sup> /m <sup>2</sup> .hr)	9	9	9	9
Oxygen flux (m <sup>3</sup> /m <sup>2</sup> .hr)	1.89	1.89	1.89	1.89
Air Injection Rate (l/min)	6	6	6	6
Water Air Ratio (m <sup>3</sup> /m <sup>3</sup> )	0	0.0042	0	0.0042
Water injection rate (l/min)	0	0.025	0	0.025
Initial Temperature (Deg C)	18	17	18	17
Operating pressure (psig)	25	25	25	25
Well Type	HI-HP	HI-HP	HI-HP	HI-HP
Well Configuration	Line Drive	Line Drive	Line Drive	Line Drive
Back pressure set point (psig)	24.4	24.3	24.5	24.4

3

4 Legend: HI = Horizontal Injector

5 HP = Horizontal Producer

6 Following completion of each run, an analysis of the cell sand pack 4 was

7 undertaken to determine the volumetric sweep efficiency. The analysis

8 comprised a physical removal of successive vertical layers of the sandpack at

9 3 cm intervals and determining the extent of the burned zone by measuring

10 the oil and coke content. In this way the volumetric sweep of the burning front

1 was determined postmortem and compared with that obtained from the peak  
 2 temperature profiles during the run. The results of the four Runs are set forth  
 3 in Table 3.

TABLE 3

## SUMMARY OF RESULTS

Run Code	971	972	975	976
Combustion Mode	Dry	Wet	Dry	Wet
Catalyst?	no	no	yes	yes
Overall period (hrs)	12.7	7.5	12.5	7.3
Pre-ignition period (hrs)	1.98	2.00	2.30	1.98
Air injection period (hrs)	10.7	5.5	10.2	5.3
Dry phase period (hrs)	10.7	2.4	10.2	2.6
Wet phase period (hrs)	0	3.1	0	2.7
Peak temp (dry phase) (deg C)	621	625	629	627
Stabilized temp (dry phase) (deg C)	452	455	455	451
Peak temp (wet phase)(deg C)	N/A	477	N/A	468
Stabilized temp (wet phase) (deg C)	N/A	393	N/A	402
CO2 % (dry stabilized)	14.3	14.2	16.5	16.5
CO % (dry stabilized)	4.0	4.0	2.4	2.3
O2 % (dry stabilized)	1.10	1.18	0.85	0.93
CO2 % (wet stabilized)	N/A	13.9	N/A	17.1

CO % (wet stabilized)	N/A	3.5	N/A	0.3
O2 % (wet stabilized)	N/A	2.3	N/A	1.6
H2 % (calculated for 975 & 976)	N/A	N/A	1.9	5.8
CO/CO + CO2	0.220	0.200	0.130	0.017
H/C	0.73	0.71	0.44	0.33
Air to Fuel requirements (Sm3/kg)	9.485	9.544	9.457	9.810
O2 to fuel requirements (Sm3/kg)	2.00	2.00	2.00	2.06
Fuel burned (kg)	0.384	0.186	0.371	0.181
Fuel burned (% of OOIP)	9.10	4.40	8.74	4.27
Oxygen utilization % (Average)	94.8	89.0	96.0	92.3
Volumetric sweep efficiency %	40.7	43.0	39.0	38.7
Fuel combustion (kg/m3)	65	30	65	32
Air Oil ratio (m <sup>3</sup> /m <sup>3</sup> )	1328	744	1428	738
Water Air ratio (m <sup>3</sup> /m <sup>3</sup> )	0	0.0042	0	0.0042
Oil recovery % of OOIP	67.9	62.3	60.4	53.2
Water recovery % of OOIP	91.3	80.4	71.1	69.8
Combustion front velocity (m/hr)	0.016	0.024	0.015	0.022

1       The produced gas analyses provide support for occurrence of the  
2   water gas shift reaction in the catalyst zone. The reaction is:  $\text{CO} + \text{H}_2\text{O} =$   
3    $\text{CO}_2 + \text{H}_2$ . Comparing the non-catalytic and catalytic dry ISC Runs, 971 and  
4   975 respectively, the CO produced gas is 40% lower for the catalytic case  
5   (2.4% vs 4.0%).

6       Comparing the produced CO for the wet combustion cases, Runs 972  
7   and 976, the CO level is 91% lower when catalyst is present (0.31% vs  
8   3.50%).

9       The CO<sub>2</sub> levels are higher in the two catalyst Runs 975 and 976,  
10   compared with the corresponding non-catalytic Runs 971 and 972, which  
11   provides further support for the water gas shift reaction as a primary source of  
12   hydrogen in catalytic in situ upgrading.

13       The differences in recovery of the original water in place can be used  
14   to calculate the amount of hydrogen produced and consumed during in situ  
15   upgrading reactions; the result is 1.91% of the total produced gas phase for  
16   Run 975 dry catalytic ISC, and 5.8% for wet catalytic ISC Run 976.

17       The results described above make it clear that any catalyst that has  
18   water gas shift activity would be beneficial and could be employed by itself or  
19   in any proportion in admixture with the hydrotreating/HDS catalyst used in  
20   Runs 975 and 976 or other such catalyst.

21       Since the water gas shift reaction produces the hydrogen required for  
22   oil upgrading, the process can be carried out by injecting high temperature  
23   steam and carbon monoxide. A carbon monoxide source, for example,  
24   oxygen-starved combustion of natural gas, will produce a gas elevated in CO  
25   which can be injected into the reservoir. In this way the key ingredients for

1 effective in situ upgrading will be provided: these are heat, hydrogen and  
2 active catalysts.

3 Also to be noted as a benefit of catalytic ISC is the lower level of  
4 produced oxygen. Since each pair of non-catalytic and catalytic Runs were  
5 conducted under the same conditions, the oxygen reduction can be attributed  
6 to the presence of catalyst.

7 The analyses of produced oil are presented in Tables 4 and 5 for API  
8 gravity, density and viscosity at each half-hour interval.

9 The prior art toe-to-heel ISC process of Greaves and Turta provides  
10 considerable thermal upgrading as measured by the three aforementioned  
11 parameters (Runs 971 and 972), but still fall very short of the performance of  
12 the catalytic Runs 975 and 976 of the present invention. The average results  
13 are summarized in Table 6. Wet catalytic ISC improved the oil gravity from  
14 11.0 API to 20.7 API and reduced the viscosity from 100,000 cps to 46 cps.  
15 Therefore the upgraded oil at a viscosity of 46 cps will be easily pipelined  
16 without the need for a diluent. Since diluent light hydrocarbons are expensive  
17 and in short supply this is a valuable benefit of the present invention.

1  
2  
3

TABLE 4

## DRY NORMAL AND CATALYTIC

Run 971 (Dry Normal)

Run 975 (Dry Catalytic)

Time	API	Density	Viscosity	API	Density	Viscosity
0.5	11.0	0.993	100000	11.0	0.993	100000
1	11.0	0.993	100000	11.3	0.991	97780
1.5	11.0	0.993	100000	14.2	0.971	8220
2	11.1	0.992	98873	14.6	0.969	7830
2.5	12.4	0.983	20234	20.6	0.930	40
3	12.8	0.981	14060	20.5	0.931	43
3.5	15.3	0.964	7435	19.8	0.935	62
4	14.8	0.967	7675	19.5	0.937	68
4.5	14.5	0.969	8020	19.3	0.938	74
5	14.1	0.972	8430	19.2	0.939	82
5.5	14.3	0.971	8160	18.9	0.941	97
6	14.0	0.973	8570	18.6	0.943	104
6.5	13.8	0.974	9010	18.4	0.944	111
7	13.7	0.945	9035	18.3	0.945	117
7.5	13.9	0.973	8660	18.2	0.945	123
8	14.0	0.973	8550	18.5	0.943	106
8.5	13.8	0.974	8990	18.0	0.946	133
9	13.6	0.975	9050	18.3	0.945	118
9.5	13.2	0.978	9780	18.4	0.944	110
10	13.4	0.977	9580	18.2	0.945	123

10.5	13.5	0.976	9440	18.3	0.945	118
11	13.3	0.977	9630	18.1	0.946	129
11.5	13.4	0.977	9560	18.0	0.946	132
12	13.1	0.979	9820	18.3	0.945	118
12.5	13.2	0.978	9770	18.4	0.944	109
Average (3.5 – 12.5 hrs)	13.8	0.972	8903	18.7	0.948	101

1

1

TABLE 5

2

## WET NORMAL AND CATALYTIC

3

Run 971 (Dry Normal)

Run 975 (Dry Catalytic)

Time	API	Density	Viscosity	API	Density	Viscosity
0.5	11.0	0.993	100000	11.0	0.993	100000
1	11.0	0.993	100000	11.7	0.988	95760
1.5	11.0	0.993	100000	13.4	0.977	10043
2	11.2	0.967	99020	15.1	0.965	6320
2.5	14.8	0.971	7690	19.8	0.935	65
3	14.2	0.975	8210	20.4	0.932	46
3.5	13.7	0.976	9015	19.7	0.936	63
4	13.5	0.974	9460	19.6	0.936	65
4.5	13.8	0.977	9000	19.4	0.938	72
5	13.4	0.977	9560	22.2	0.930	24
5.5	13.2	0.978	9760	20.7	0.921	37
6	12.5	0.983	10170	21.4	0.925	31
6.5	13.0	0.979	9900	20.7	0.930	37
7	12.9	0.980	9960	21.0	0.928	33
7.5	12.8	0.981	10040	21.3	0.926	32
Average (2.5 – 7.5 hrs)	13.4	0.980	9342	20.6	0.931	46



1 TABLE 6  
2 SUMMARY OF UPGRADING RESULTS (AVERAGES)

Run #	Condition	API Gravity	Density g/cc	Viscosity mPa.s
Base	no ISC	11.0	0.993	100,000
971	Dry Normal	13.8	0.972	8,903
975	Dry Catalytic	18.7	0.948	101
972	Wet Normal	13.4	0.980	9,342
976	Wet Catalytic	20.7	0.931	46

3  
4 Further important upgrading benefits are demonstrated in Table 7,  
5 where XT004466 is clean dry Wolf Lake crude oil which was used in the four  
6 test Runs 971, 972, 975 and 976, and XT004467 is produced oil from the wet  
7 catalytic Run 976 of the present invention.

8 An extensive desulfurization and demetalization of the base oil was  
9 achieved in the catalytic Run 976 of the present invention. Sulfur was  
10 reduced 88% from 43,400 ppm to 5,100 ppm; nickel 96% from 73 ppm to 3  
11 ppm and vanadium 96% from 195 ppm to 8 ppm. Other metals, such as iron  
12 and molybdenum were also partially removed in the catalytic process. It  
13 should be noted that the increase in silicon is not a consequence of the  
14 presence of catalyst: all high temperature steam processes give rise to  
15 elevated silicon levels.

1

TABLE 7

2

OIL SULFUR AND METAL ANALYSIS (by ICP, mg/kg)

Sample ID	XT004466 (10 API)	XT004467 (20.7 API)
Customer ref:	Base Wolf Lake oil	Run 976 product
Silver	<1	<1
Aluminum	<1	<1
Boron	2	3
Barium	<1	<1
Calcium	2	2
Chromium	<1	<1
Copper	<1	<1
Iron	5	<1
Potassium	<8	<8
Magnesium	1	<1
Manganese	<1	<1
Molybdenum	7	3
Sodium	<6	<6
Nickel	73	3
Phosphorus	<2	<2
Lead	<2	<2
Sulphur	43400	5100
Silicon	1	69
Tin	<2	<2
Titanium	1	<1

Vanadium	195	8
Zinc	2	5

1

2           Figure 5 shows gas chromatographic analyses of samples XT 004466  
3   Wolf Lake crude oil and Run 976 wet catalytic ISC product. Very extensive oil  
4   upgrading is apparent from the large decrease in heavy components  
5   observed in the catalytic Run.

6           The wet combustion test of Run 976 demonstrated the preferred form  
7   of the invention. Either moderate wet combustion or superwet combustion  
8   may be applied. However, in oil reservoirs where water injectivity is too low,  
9   the catalytic dry combustion process may be applied as well.

#### 10   TEST OF NCC TYPE CATALYST

11   Run 986 was conducted using NCC catalyst placed around the horizontal leg  
12   of the producer for the purpose of comparison with an otherwise identical non-  
13   catalytic Run 985.

14           The original test cell was modified to have 6-band heaters and  
15   computer control to provide a better approach to adiabatic conditions.

16           The catalytic Run 986 used the catalyst FCC-RESOC-1 BU, a rare  
17   earth alumino silicate supplied by Grace Davison, and having the following  
18   physical characteristics.

19   Composition	42%A1203, 1.0% Rare Earth oxide,
20	0.2% Na <sub>2</sub> O
21   Surface area (square meters/gm)	300
22   Bulk density (g/ml)	0.7
23   Average particle size (microns)	72

1 Results showed that the Run 986 with NCC catalyst produced Wolf  
2 Lake oil (11 API) of 21.0 degrees API, which was 7 degrees API higher than  
3 the thermally cracked oil in the absence of catalyst in Run 985.

4 The effect of vertical heterogeneity of the reservoir on fluid channeling  
5 was tested in a specially-packed cell in Run 7. Three layers of sand were  
6 packed sequentially using fine, coarse and fine-grained sands to see whether  
7 air would advance ahead of the vertical combustion front in the high-  
8 permeability central layer. Table 8 gives the details of the stratified model.  
9 Figures 8a – 8f shows the results in terms of thermal contours. The vertical  
10 axis represents temperature in all cases. Lowest temperatures are shown in  
11 dark color. The combustion front remained substantially vertical, with no  
12 preferred advancement into the central zone. The explanation may be that  
13 the vertical drainage of the hot cracked oil provides a "self-healing"  
14 phenomenon where air advancement into the central high permeability streak  
15 is blocked by draining oil. This demonstrates that the process of the present  
16 invention has a major advantage over processes of the prior art in which both  
17 the injected air and produced fluids flow substantially horizontally between  
18 vertical wells and fingering of air into high permeability layers causes early  
19 oxygen breakthrough and safety hazards. Layers of varying permeability are  
20 a very common feature of clastic reservoirs and often prohibits the use of  
21 traditional in situ combustion as an oil recovery process. The present  
22 invention removes this limitation.

TABLE 8

RUN 7

DRY IN SITU COMBUSTION IN A STRATIFIED MODEL; CLAIR OIL, 19.8

API, 200 CPS AMBIENT

Layer	Sand Grain Size	Permeability MD
Top	fine	616
Middle	coarse	3000
Bottom	fine	616

In the preferred field embodiment of the invention, the direct line-drive application illustrated in Figures 6 and 7, a reservoir 100 is characterized by a downward dip and lateral strike. A row 101 of vertical air-water injection wells 102 is completed high in the reservoir 100 along the strike. At least two rows 103, 104 of production wells 105, 106 having generally horizontal legs 107, are completed low in the reservoir and down dip from the injection wells, with their toes 108 closest to the injection wells 102. The toes 108 of the row 103 of production wells 105 are spaced down dip from a vertical projection of the injection wells 102. Catalyst particles are emplaced along the horizontal well by a well-known operation called "gravel packing". The second row 104 of production wells 106 is spaced down dip from the first row 103, and is similarly gravel packed. Generally, the distance between wells, within a row, is considerably lower than the distance between adjacent rows. In the first phase of the process, a generally linear combustion front is generated in the reservoir 100 by injecting air or air-water through every second well 102.

1 Preferably a generally linear lateral combustion front is developed by initiating  
2 combustion at every second well and advancing these fronts laterally until the  
3 other wells are intercepted by the combustion front and by keeping the  
4 horizontal production wells closed. Then, air is injected through all the wells  
5 102 in order to link these separate fronts to form a single front. Only during  
6 this initiation phase of the field exploitation process, and only once in the  
7 lifetime of a producing reservoir, is non-upgraded oil produced. The front is  
8 then propagated by injecting air and water down dip toward the first row 103  
9 of production wells 105. The horizontal legs of the production wells 105 are  
10 generally perpendicular to the front. The production wells 105 are open  
11 during this step, to create a low pressure sink to induce the front to advance  
12 along their horizontal legs 107 and to provide an outlet for the heated oil.  
13 When the front approaches the heel 109 of each production well 105, the well  
14 is closed in. The horizontal legs 106(107) of the closed-in wells 105 are then  
15 filled with cement. The wells 105 are then perforated high in the reservoir 100  
16 and converted to air-water injection, thereby continuing the propagation of a  
17 combustion front toward the second row 104 of production wells 106.  
18 Preferably, the first row 101 of injection wells is converted to water injection,  
19 for scavenging heat in the burnt out zone and bringing it ahead of the  
20 combustion zone. This process is repeated as the front progresses through  
21 the various rows of production wells. By the practice of this process, a guided  
22 combustion front is caused to move through the reservoir with good  
23 volumetric sweep efficiency, and the production of upgraded oil.

1. A process for upgrading hydrocarbons in-situ in an underground reservoir having hydrocarbons, comprising the steps of:

- 5 (a) providing at least one injection well for injecting an oxidizing gas into the underground reservoir;
- (b) providing at least one production well having a substantially horizontal leg and a substantially vertical production well connected thereto, wherein the substantially horizontal leg extends toward the injection well, the horizontal leg having a heel portion in the vicinity of its connection to the vertical production well and a toe portion at the opposite end of the horizontal leg, wherein the toe portion is closer to the injection well than the heel portion;
- 10 (c) providing an oil upgrading catalyst between the toe portion and the heel portion substantially coextensive with at least a portion of the horizontal leg;
- 15 (d) injecting the oxidizing gas through the injection well for in-situ combustion, so that combustion gases are produced;
- (e) thermally upgrading the hydrocarbons in a first in-situ upgrading phase of the process, wherein the combustion gases initially contact the hydrocarbons in the vicinity of the toe portion of the horizontal leg;
- 20 (f) catalytically upgrading at least a portion of the hydrocarbon thermally upgraded in step (e) in a second in-situ upgrading phase of the process, wherein at least a portion of the hydrocarbons thermally upgraded in step (e) and at least a portion of the combustion gases initially contact the oil upgrading catalyst in the vicinity of the toe portion of the horizontal leg;
- 25 and
- (g) progressively thermally and catalytically upgrading hydrocarbons, wherein
- 30 (i) the combustion gases progressively advance as a front, substantially perpendicular to the horizontal leg, in a direction from the toe portion to the heel portion and
- (ii) the oil upgrading catalyst is progressively consumed substantially in a direction from the toe portion to the heel portion of the horizontal leg.

2. The process of claim 1 wherein the oil upgrading catalyst is provided in packing around the horizontal leg of the production well.
3. The process of claim 1 wherein the horizontal leg of the production well is coated with the oil upgrading catalyst.
4. The process of claim 1 wherein the oil upgrading catalyst is provided in packing inside the horizontal leg of the production well.
5. The process of claim 1 wherein the oil upgrading catalyst comprises a hydrodesulfurizing catalyst.
6. The process of claim 1 wherein a water-gas shift catalyst is used in combination with the oil upgrading catalyst.
7. The process of claim 1 wherein the oxidizing gas comprises air.
8. The process of claim 1 wherein a reducing gas is injected through the injection well.
9. The process of claim 8 wherein the reducing gas is selected from carbon monoxide, hydrogen and a combination thereof.
10. The process of claim 1 wherein a substantially linear array of substantially vertical injection wells is used for injecting oxidizing gas.
11. The process of claim 10 wherein the reservoir extends downwardly at an angle to have a dip and a strike, the injection wells extend generally along the strike and the horizontal leg of the production well extends generally along the dip.
12. The process of claim 10 wherein the reservoir extends downwardly at an angle to have a dip and a strike, a plurality of production wells, each connected to horizontal legs, are provided in at least two spaced apart rows parallel with the array of injection wells, and the rows of injection wells and production wells



extend generally along the strike and the horizontal legs of the production wells  
extend generally along the dip.

13. The process of claim 12 wherein the wells are arranged in a staggered line.

5

14. The process of claim 12 wherein the wells are arranged in a direct line drive  
configuration.

15. The process of claim 12, further comprising the steps of:

10

(h) closing each production well in the first row as the combustion front  
approaches the heel of its respective horizontal leg;

(i) filling the horizontal legs of the closed production wells in the first row with  
cement;

15

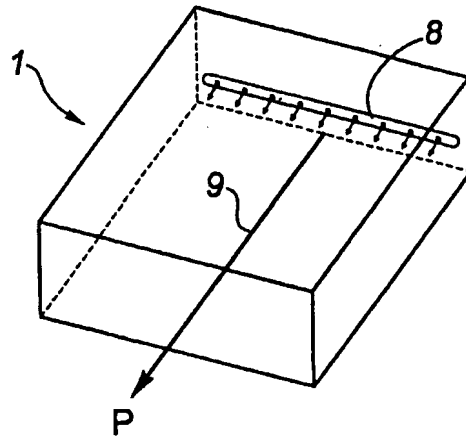
(j) re-completing the wells relatively high in the reservoir and converting  
them to injection wells for injecting oxidizing gas; and

(k) repeating steps (d) through (g).

16. The process of claim 1 wherein the injection well is a horizontal well having a  
horizontal portion perpendicular to the horizontal leg of the production well.

20

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PRIOR ART

FIG. 1

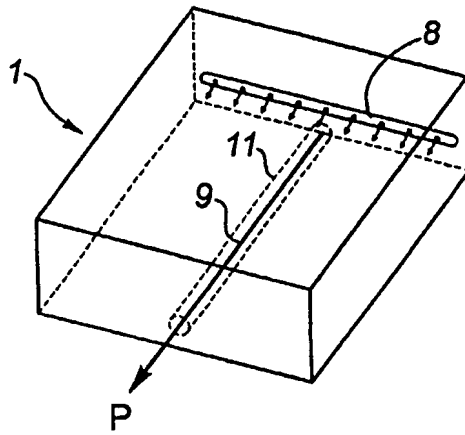
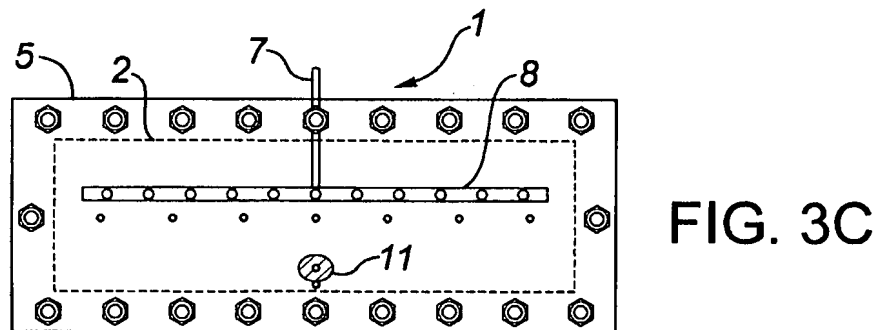
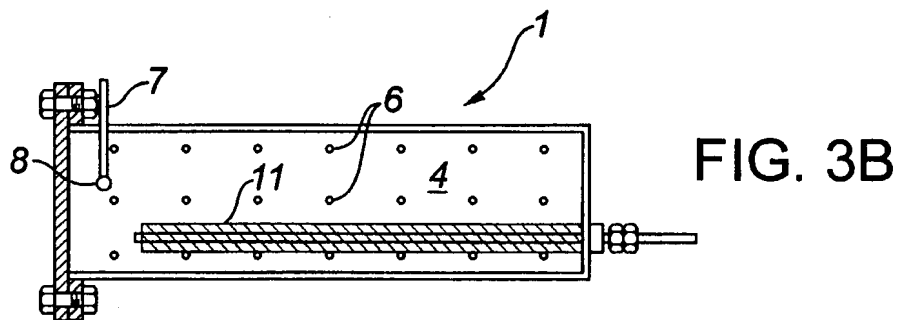
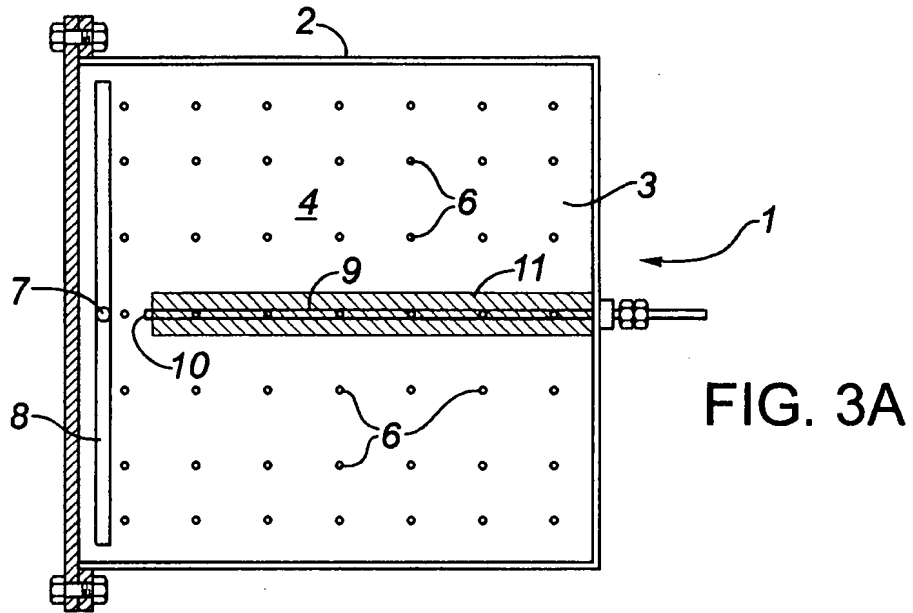


FIG. 2

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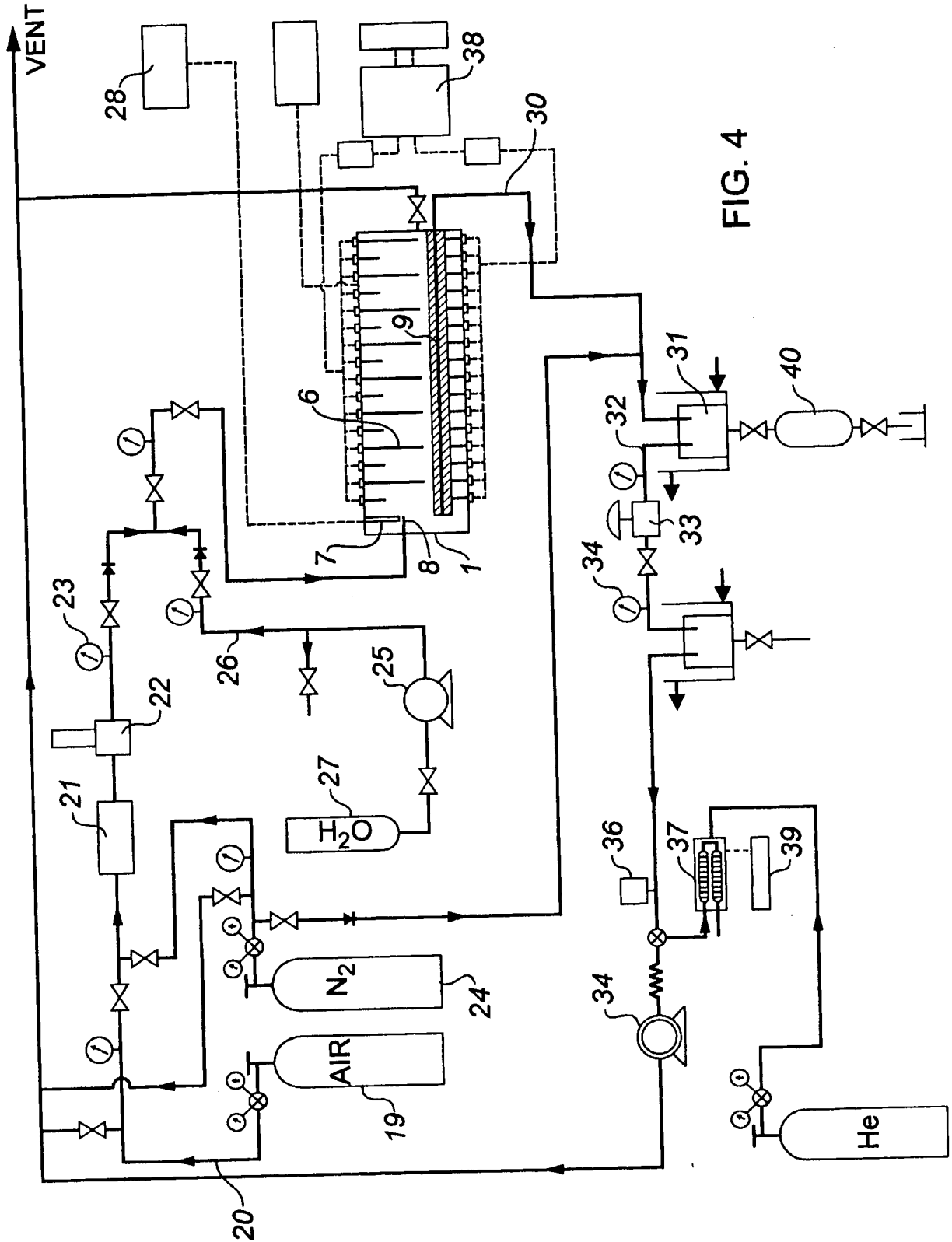


FIG. 4

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FIG. 5A

BASE WOLF LAKE OIL

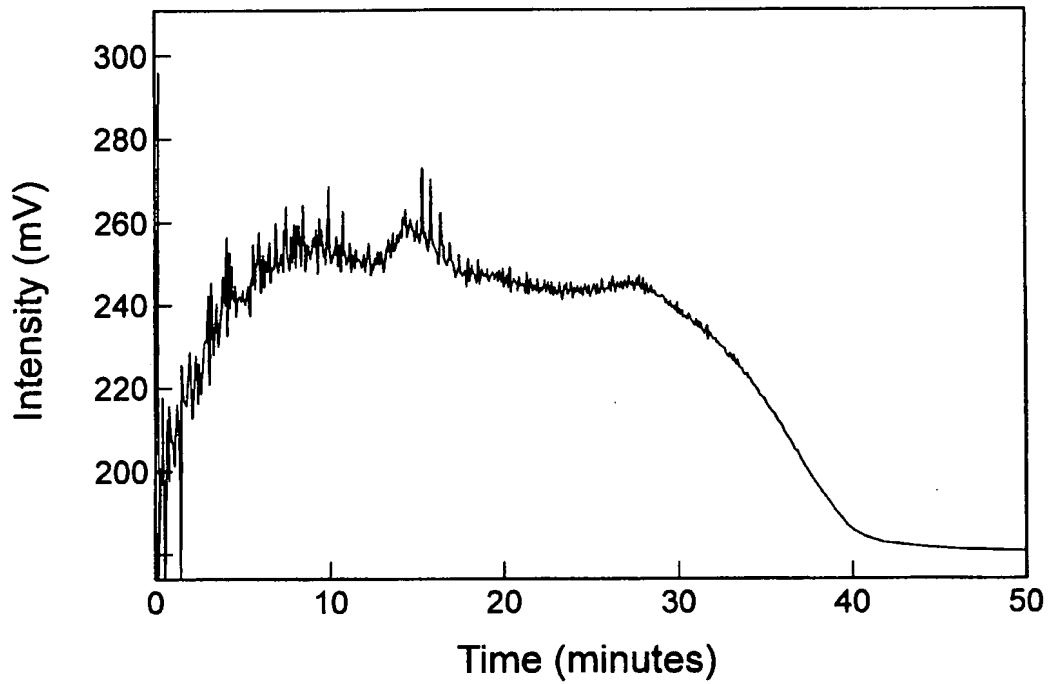
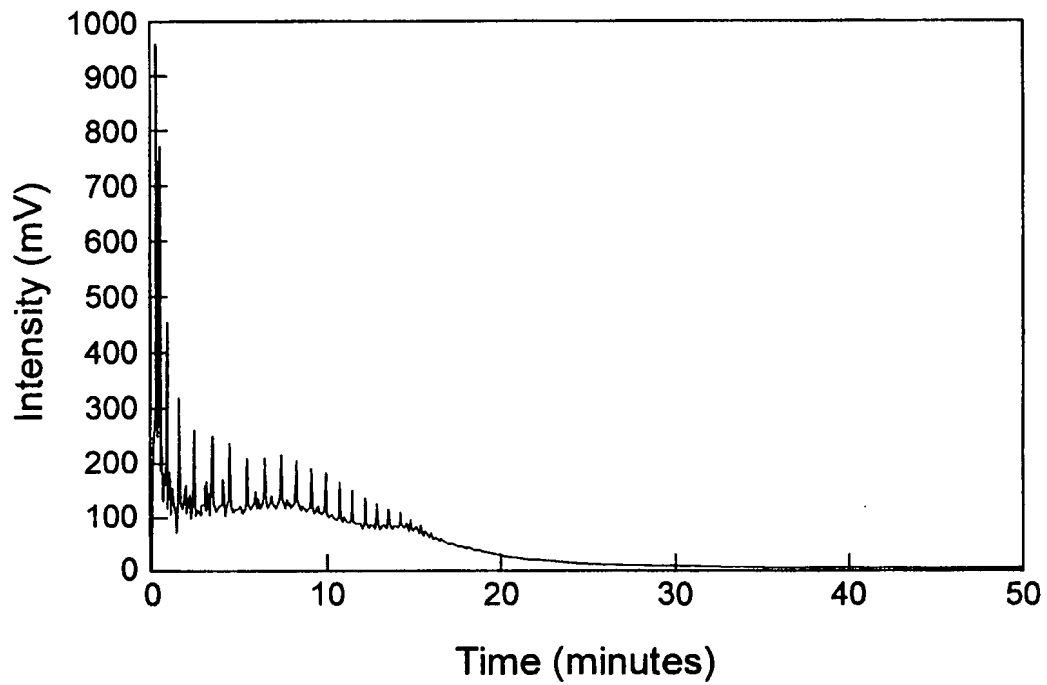


FIG. 5B

WET CATALYTIC ISC RUN 976



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FIG. 6

UPSTRUCTURE FAULT

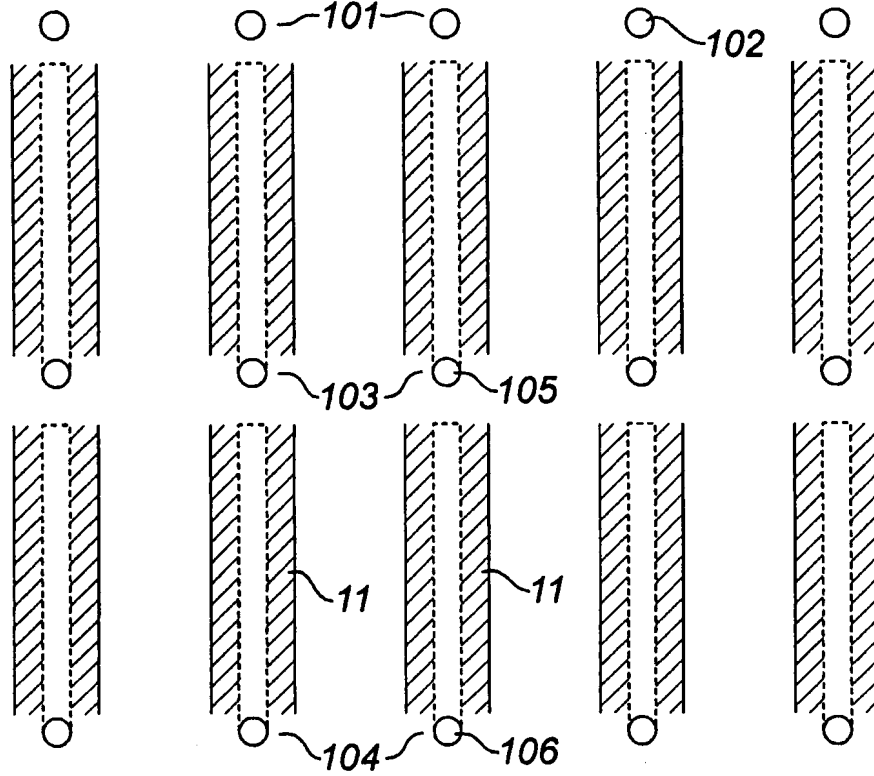
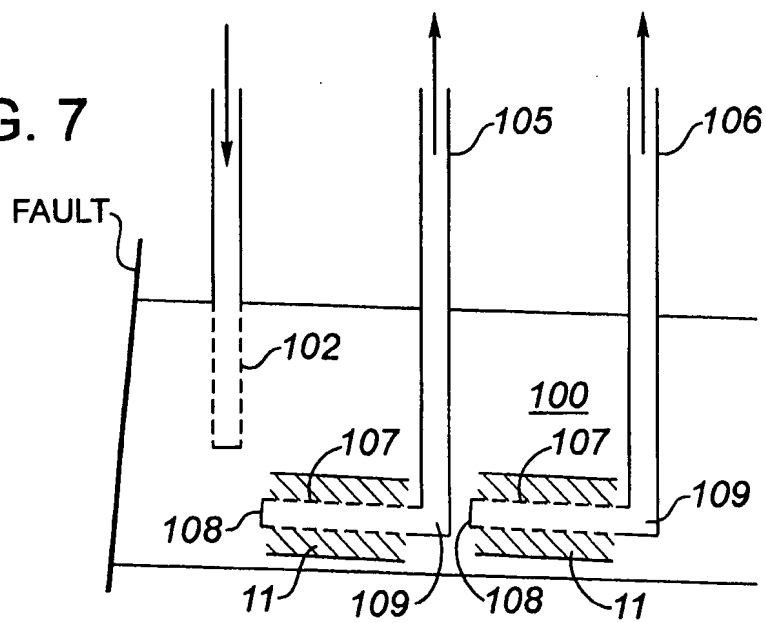


FIG. 7



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FIG. 8A

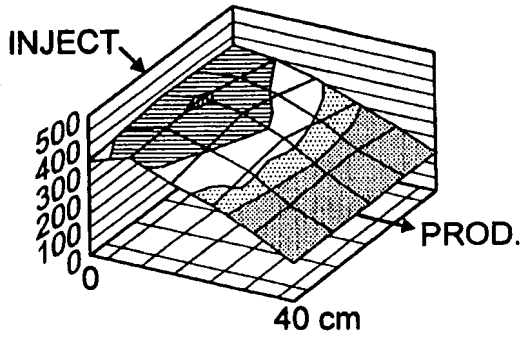


FIG. 8B

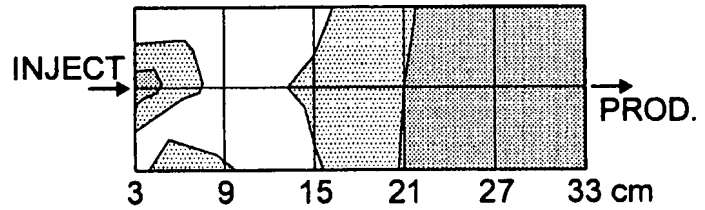


FIG. 8C

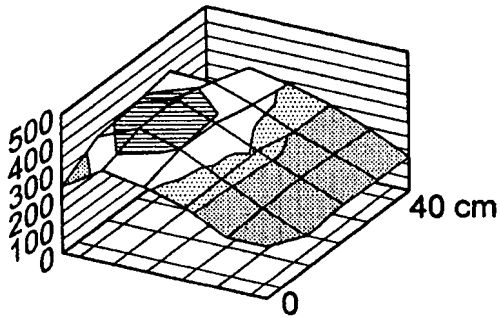


FIG. 8D

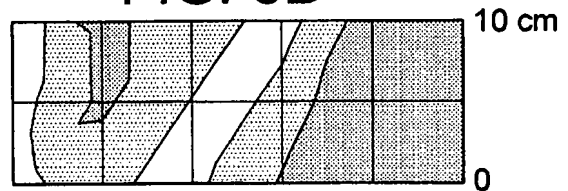


FIG. 8E

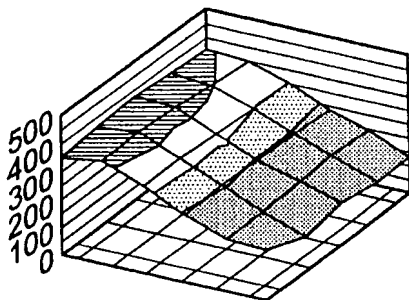


FIG. 8F

